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Instantaneous Effects of Sediment Resuspension on Inorganic and Organic Benthic Nutrient Fluxes at a Shallow Water Coastal Site in the Gulf of Finland, Baltic Sea

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Abstract
Climate change is leading to harsher resuspension events in shallow coastal environments influencing benthic nutrient fluxes. However, we lack information on the quantitative connection between these fluxes and the physical forces. Two identical experiments that were carried out both in May and August provided novel knowledge on the instantaneous effects of resuspension with known intensity on the benthic dissolved inorganic (phosphate: DIP, ammonium: NH_4^+, nitrite+nitrate: NO_x, silicate, DSi) and organic nutrient (phosphorus: DOP, nitrogen: DON, carbon: DOC) fluxes in the shallow soft bottoms of the archipelago of Gulf of Finland (GoF), Baltic Sea. Resuspension treatments, as 2 times the critical shear stress, induced effluxes of one to two orders of magnitude higher than the diffusive fluxes from the studied oxic bottoms. The presence of oxygen resulted in newly formed iron oxyhydroxides and the subsequent precipitation/adsorption of the redox-dependent nutrients (DIP, DSi, organic nutrients) affecting their fluxes. Resuspension-induced NH_4^+ and NO_x fluxes were associated with the organic content of sediments showing the highest values at the organic rich sites. NH_4^+ showed the strongest responses to resuspension treatments in August, but NO_x at the time of high oxygen concentrations in near-bottom water in May. Foreseen increases in the frequency and intensity of resuspension events due to climate change will most likely enhance the internal nutrient loading of the studied coastal areas. The fluxes presented here, connected to known current velocities, can be utilized in modeling work and to assess and predict the internal nutrient loading following climate change.

Keywords Sediment resuspension · Benthic flux · Inorganic and organic nutrients · Critical shear stress

Introduction

Shallow coastal areas function as buffer zones for nutrients entering a marine ecosystem from its catchment. Sediment resuspension caused by surface waves and near-bottom currents is a common phenomenon that has implications on mineralization and recycling of benthic nutrients of shallow coastal areas (e.g., Sloth et al. 1996; Thomsen et al. 2002; Ståhlberg et al. 2006; Capet et al. 2016). Altered nutrient recycling may in turn affect the productivity of overlying waters (e.g., Fanning et al. 1982; Porter et al. 2010). Although the different effects of resuspension on nutrient cycling in the coastal areas have been studied, the quantification of the effects of sediment resuspension on sediment-water fluxes needs additional attention, since shallow area sediments supply significant amounts of limiting nutrients to primary producers globally (Boynton et al. 2018).

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Resuspension occurs when a critical shear stress, a force needed to initiate movement of surface sediment particles, is exceeded (e.g., Sheng and Lick 1979). In future, resuspension events are foreseen to occur more frequently and to be stronger in the marine shallow coastal areas including those of the Baltic Sea (Räisänen et al. 2004; Danielsson et al. 2007). Due to increased wind activity and possible change in the direction of prevailing winds, most critical impacts may occur in areas where the bottom sediments are currently more or less sheltered (Danielsson et al. 2007) and even minor strengthening of winds may markedly increase resuspension in shallow areas (Jönsson 2005). This is especially relevant for the shallow Baltic Sea where 25% of the total area is shallower than 20 m, and for its strongly eutrophied sub-basin, Gulf of Finland (GoF) (mean depth 38 m) (e.g., Andersen et al. 2015). Additionally, climate change is expected to increase the external nutrient loading from the catchment areas to the estuarine and coastal areas of the Baltic Sea due to increased annual and especially winter runoff and shortened snow cover period (Schneider et al. 2013; Huttunen et al. 2015). This emphasizes the crucial roles of the physical and chemical processes affecting the cycling of nutrients between sediment and water in coastal areas. Therefore, it is important to gain knowledge of the current prerequisites for sediment resuspension as well as the effects of sediment disturbance on benthic nutrient cycling. Such knowledge is valuable e.g. for different model assessments used for predicting internal nutrient loadings in the shallow coastal areas of the Baltic Sea in a changing climate.

GoF has a wide, fragmented archipelago on its northern shore (Winterhalter et al. 1981; Virtasalo et al. 2005; Jilbert et al. 2017). The archipelago s geographical complex shape and varying bathymetry together with physical forces, waves, and currents have created a mosaic like bottom sediment showing great spatial differences in water and organic content and grain sizes. Shallow bottoms of the archipelago differ in susceptibility to sediment resuspension depending on the direction and velocity of winds that create surface waves, water currents, and upwelling events, which drive resuspension (e.g., Haapala 1994). In the GoF archipelago, as in other shallow water areas of the Baltic Sea, sediment resuspension has been shown to affect the benthic nutrient fluxes as well as being responsible for the flux of sediment-bound main nutrients (such as carbon, nitrogen, and phosphorus) from shallow to deeper waters (Floderus and Håkanson 1989; Christiansen et al. 1992; Heiskanen et al. 1998; Niemistö et al. 2018). Consequently, the susceptibility of sediments for resuspension and the nutrient retention capacity of sediments influence the magnitude of internal loading and fluxes of nutrients into the water column and to the deeper basins of the Baltic Sea (Christiansen and Emelyanov 1995).

Benthic dynamics of some inorganic nutrients, such as dissolved inorganic phosphorus (DIP) and dissolved silicate ($Si(OH)_4$, hereafter DSi), depends on the physico-chemical conditions (redox potential, sorption-desorption reactions) at the sediment-water interface, in which resuspension may induce changes. Resuspension-induced oxygenation of surface sediments produces iron oxyhydroxides, which can bound DIP and DSi (Anderson and Benjamin 1985; Pant and Reddy 2001; Sundby et al. 1986; Niemistö et al. 2018). Additionally, resuspension affects the sorption-desorption reactions on particle surfaces by altering the nutrient concentrations in the ambient solution (Koski-Vähälä and Hartikainen 2000; Tallberg et al. 2008). Dissolved organic nutrients also strongly associate with particles in coastal waters (Asmala et al. 2014; Jilbert et al. 2017). Their benthic fluxes may be affected by resuspension-produced iron oxyhydroxides that can efficiently adsorb these nutrients (Dzombak and Morel 1990; Eusterhues et al. 2008; Skoog and Arias-Esquivel 2009). Benthic fluxes of ammonium (NH_4^+) and nitrite+nitrate (NO_x) can be altered due to resuspension (Spagnoli and Bergamini 1997; Morin and Morse 1999; Niemistö et al. 2018). This is because microbial-mediated transformation pathways of nitrogen either require the presence (nitrification) or absence (denitrification) of oxygen (e.g., Thamdrup and Dalsgaard 2008), whose benthic fluxes may be affected by resuspension (Almroth et al. 2009; Almroth-Rosell et al. 2012; Moriarty et al. 2017; Niemistö et al. 2018). Although resuspension evidently alters the benthic nutrient fluxes in the Baltic Sea (e.g., Almroth et al. 2009; Almroth-Rosell et al. 2012; Niemistö et al. 2018), there is a lack of knowledge on the exact critical forces and water current velocities that initiate these resuspension events, as well as on the quantitative connection between water current velocities and the magnitude of benthic fluxes in an archipelago area.

This study was conducted in the archipelago of the GoF, Baltic Sea, in fairly sheltered soft sediments which encounter episodic resuspension events in the present climatic conditions. The sediments that vary in water and organic content were studied to determine the critical shear stresses and the instantaneous effects of resuspension on benthic nutrient fluxes. The resuspension induced with known force was hypothesized to significantly increase the benthic fluxes of inorganic and organic nutrients to the water column, and thus their supply for primary producers during the pelagic productive season.

Material and Methods

Study Area

The study was conducted in the archipelago of Gulf of Finland near the Hanko Peninsula. Rapid displacements of various water masses caused by fluctuations in meteorological conditions are common in the study area and due to this, the area is influenced by the surface water with different salinities (Gulf of Finland: salinity 5–6 practical salinity units (psu); inner archipelago: 3–5 psu; upwelling deep water: 7 psu) (Niemi 1975). Four stations were sampled over two seasons, spring and summer, to cover the important periods for pelagic production. Three of the study stations (1–3) were located in the semi-enclosed bay Storfjärden and the fourth station (4) was located on the outer edge of the archipelago (Fig. 1). All the study stations were fairly sheltered from the prevailing southwestern winds. The stations that differed in depth were chosen to cover bottom areas with different sediment characteristics (e.g., grain size, water, and organic content) with oxygen present in the bottom water (in situ measurements 0.5 m above the bottom) through the productive season (Tables 1 and 2).

Experimental Design

Sediment Sampling and Critical Shear Stress Measurements

From each station, undisturbed sediment cores were collected with an HTH gravity corer (Pylonex, Umeå, Sweden, inner diameter 86 mm) (Renberg and Hansson 2008). The samples were moved to the experimental columns of the LABEREX chamber at the field (transparent polycarbonate core, height 30 cm, inner diameter 84 mm) (Lund-Hansen et al. 1999) in such a way that approximately 13-cm-high water column was left on top of the 15-cm-high undisturbed sediment core. During the short transportation to the laboratory (less than 15 min), the samples were kept cold and dark in a cool box with ice packs (approx. less than ± 2 °C deviation to in situ temperature).

For each station, critical shear stress (τ_{crit}) was determined (at in situ temperature 4.0–5.0 °C in May; 5.4–20.5 °C in August) from four replicated cores that were collected 14 h prior to the determinations (on 2 May and 3 Aug in 2014). Before the critical shear stress measurements, the height of the water in the experimental column was adjusted to 10 cm. For this volume, the hydrodynamics of the chamber is known. The critical shear stress measurements are based on the known current velocities induced by the rotation of the four bladed impeller and the light beam attenuation due to resuspended particles in the experimental chamber with the sediment. A software (PC) is used for controlling the rotation velocity of the impeller and for recording the light beam (633 nm) attenuation data (see more in detail Lund-Hansen et al. 1999). Critical current velocities at 100 cm from the bottom (U_{100}) were calculated by the equation (e.g., Lund-Hansen et al. 1997):

$$\tau_{crit} = C_d \cdot \rho_w \cdot U_{100}^2 \quad \left(\mathrm{N\ m^{-2}}\right); \tag{1}$$

where

- C_d Drag coefficient (0.003, muddy sand)
- ρ_w Water density (kg m^{-3})
- U_{100} Current velocity (m s^{-1}) 1 m above the bottom

Sediment Core Incubations and Nutrient Flux Determinations

Each station was sampled on a separate date in spring (5–8 May) and summer (4–7 Aug) in 2014. Seven sediment cores were collected from each station for the nutrient experiments as described above. Three of the samples were used as control columns (C-columns) and in four of the samples resuspension (R-columns) was induced with the strength of 2 × τ_{crit} termed U. This is the current speed at 1 m above the sediment equal to a 2 times higher critical shear stress. The sampling and treatment for the columns were conducted in a dark tempera-